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ORIGINAL PAPER

Nitrogen in soils beneath 18–65 year old stands of subtropical evergreen broad-leaved forests in Laoshan Mountains in Eastern China

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Abstract: Monitoring of soil nitrogen (N) cycling is useful to assess soil quality and to gauge the sustainability of management practices. We studied net N mineralization, nitrification, and soil N availability in the 0–10 cm and 11–30 cm soil horizons in east China during 2006–2007 using an in situ incubation method in four subtropical evergreen broad-leaved forest stands aged 18-, 36-, 48-, and 65-years. The properties of surface soil and forest floor varied between stand age classes. C:N ratios of surface soil and forest floor decreased, whereas soil total N and total organic C, available P, and soil microbial biomass N increased with stand age. The mineral N pool was small for the young stand and large for the older stands. NO_3^--N was less than 30% in all stands. Net rates of N mineralization and nitrification were higher in old stands than in younger stands, and higher in the 0–10 cm than in the 11–30 cm horizon. The differences were significant between old and young stands ($p < 0.031$) and between soil horizons ($p < 0.005$). Relative nitrification was somewhat low in all forest stands and declined with stand age. N transformation seemed to be controlled by soil moisture, soil microbial biomass N, and forest floor C:N ratio. Our results demonstrate that analyses of N cycling can provide insight into the effects of management disturbances on forest ecosystems.

Keywords: microbial biomass nitrogen; nitrogen availability; nitrogen mineralization; soil horizon; subtropical forest

Introduction

Knowledge of soil nitrogen (N) dynamics is critical to understanding the effects of forest management practices on long-term soil productivity, a topic that has been of concern for decades (Pérez et al. 2004; Yan et al. 2008). Forest management activities, such as harvesting, thinning, and site preparation, may change soil structure, micro-environmental conditions, substrate availability, and, ultimately, N dynamics (Li et al. 2003; Lindo and Visser 2003). Monitoring of nutrient cycling is a useful method to assess overall soil quality and to gauge the sustainability of management practices (Morris and Boerner 1998; Lindo and Visser 2003; Mikha et al. 2006).

Soil N mineralization is affected by both biotic and abiotic factors (Vervaet et al. 2002; Bengtsson et al. 2003), and by management practices (Zaman and Chang 2002; Yan et al. 2008). Timber harvesting is a major disturbance in forest ecosystems. Timber harvest changes stand structure and environmental conditions, and this impacts N cycling (e.g. Crow et al. 1991; Schilling et al. 1999; Pérez et al. 2004; Yan et al. 2008). Knowledge of the relative quantities of organic and inorganic N, their process rates, and the main regulators of these parameters over time (e.g. Marques et al. 1997; Piatek and Allen 1999; Idol et al. 2003) can provide substantial insight into the impacts of forest development on soil N status and ecosystem function (Verchot et al. 2001; Corre et al. 2006).

In order to understand the impacts of forest development after harvesting on ecosystem properties, space-for-time substitution is usually used as an evaluation method. Researchers have investigated nutrient cycling across a range of stand ages from harvest to maturity (Hughes and Fahey 1994; Marques et al. 1997; Pérez et al. 2004), but no studies are reported from the subtropical evergreen broad-leaved forests in east China. Subtropical evergreen broad-leaved forest is the most widely distributed land-cover type in east China and it supports high species richness. These forests are also among the most heavily utilized by humans. Song and Chen (2007) estimated that less than 15% of the area originally covered by evergreen broad-leaved forests remained intact by the end of the 1980s. This type of forest is among the least studied of subtropical forest ecosystems.

The purpose of our research program was to monitor N cycling from litter production and decomposition to N mineralization and uptake at stages of forest development after harvesting.

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The present study focuses upon N pool, N mineralization, and nitrification in forest stands at subsequent stages of development following harvesting. Through this research we attempt to describe relationships between these N cycling processes and environmental conditions such as soil and forest floor properties.

Materials and methods

Study site

The study was conducted at Laoshan Nature Reserve in Anhui, Eastern China (30°20′ N, 117°39′ E, 110–900 m a.s.l.). The climate of this region is subtropical monsoon with a hot and humid summer and a dry and cold winter. The mean annual temperature is 16.4°C, with the lowest temperature of 3.6°C in January and the highest temperature of 28.2°C in July. The average annual precipitation is 1 550 mm (range from 1 220 mm to 1 890 mm) concentrated from May to August.

We selected four upland evergreen broad-leaved forest stands that represented different stages of stand development. All stands were located within 1 km of each other. Overstory tree species were dominated by evergreen broad-leaved trees such as *Castanopsis sclerophlla* Schott., *C. eyrei* Tutch., *Cyclobalanopsis glauca* Oerst., *Lithocarpus glaber* Makai., and deciduous broad-leaved species *Liquidambar formosana* Hance. The tree canopy was 10–20 m high and coverage was 80%–90%. The shrub layer was <3.0 m and coverage was 25%–40%. The herb layer was <1 m with coverage of 10%–30%, and the dominant herbs were typically ferns. All four stands were subjected to commercial harvesting followed by clear-cutting of remaining overstory trees. Regeneration was allowed to proceed naturally. Vigorous regrowth of seed-dispersed pioneer trees, and tree stump and root sprouts is common on sites in this region. Permanent sampling plots (30 m × 20 m) were set up at the centre of each stand to eliminate edge effects. Between September and November 2005, we identified and tagged every tree rooted within the plots that had a trunk diameter at breast height (DBH) ≥ 3.0 cm . A full description of the flora and vegetation structure of stands is given by Lan et al. (2008). Stand age was based on tree-ring counts of at least 15 canopy trees per stand. The general characteristics of the sampling stands are given in Table 1.

The substrate parent materials were acidic intrusive rocks composed of sandstone and granite. The soil texture was mainly sandy loam with a granular structure on well-drained and steep slopes (24–36°), and soil pH ranged from 4.4 to 5.3 (Xu et al. 2009). All stands were located on soil of shallow reddish yellow soils (<1 m deep), classified as Haplic luvisols (Soil Survey Staff 1999).

N mineralization and nitrification measurements

We set up six 3 m × 3 m subplots for soil sampling at randomly selected locations within each plot. In each subplot, we established three sampling points. At each sampling point, samples of both surface (0–10 cm) and deep (11–30 cm) soil horizons were collected using an auger with an internal diameter of about 6.0 cm. Soils collected within each subplot combined to yield a single composite sample. Soil sampling was conducted seasonally (four times per year: February, April, July and October) over two years beginning in February 2006.

Table 1. Structural characteristics and site conditions of successional stands in Laoshan Nature Reserve in Eastern China

Stand age (year after harvesting)	Altitude (a.s.l., m)	Slope (°)	Aspect (°)	Soil depth (cm)	Soil texture	Mean DBH (cm)	Mean tree Height (m)	Density (Stems·ha^{-1})	Basal area (m^2·ha^{-1})	Undergrowth coverage (%)
18 year	235	28	S11E	50	sandy loam	6.5	7.7	4152	24.53	20
36 year	185	31	S8W	50	sandy loam	8.7	9.2	3465	29.16	35.2
48 year	250	26	W17S	70	sandy loam	12.7	11.3	3076	53.72	30.5
65 year	280	35	S13W	52	loam	16.7	12.9	2492	65.39	37.6

Samples of surface and deep soil horizons were separately sieved through a 5-mm mesh to separate roots and the gross fraction of soil. Each composite sample was then divided into two subsamples. One subsample was transported in a cooler on ice back to the laboratory to determine the initial NH_4^+ and NO_3^- contents and soil microbial biomass N. The second subsample was placed in a polyethylene bag and returned to the soil at the same location and depth of collection. Field incubated samples were retrieved after 35–40 days and taken to the laboratory to determine the final NH_4^+ and NO_3^- contents. The samples were stored in a refrigerator at 4°C until analyzed, usually within three days.

The inorganic-N concentrations were expressed on a dry-weight basis. Subsamples of 15 g were extracted in 50 ml of 2 mol·L^{-1} KCl for 1 h and filtered through Whatman GF/F glass microfiber filters. NH_4^+-N and NO_3^--N were then analyzed with a flow-injection autoanalyser (FOSS FIA Star 5000) using alkaline phenol and cadmium reduction techniques, respectively. Net N mineralization was calculated as the change in extractable (NH_4^+ and NO_3^-)-N concentration during incubation. Soil net nitrification was calculated as the change in extractable NO_3^--N concentrations during incubation. Net N mineralization rate and soil net nitrification rate were expressed as the net mineralization (or nitrification) per gram of soil per day. Another subsample (about 20 g) was placed in a 105°C oven for >12 h to obtain an oven-dry weight.

A fumigation-extract method was used to quantify soil microbial biomass N (SMBN) (Brookes et al. 1985). Two sub-samples of fresh mineral soil (ca. 30 g) were extracted with 100 ml of 0.5 mol·L^{-1} K_2SO_4. The samples were shaken for 40 min, then fil-

tered. Simultaneously, two other sub-samples of soil were fumigated with ethanol-free chloroform for 24 h at 25°C and then extracted. The total N in the extracts was immediately determined by TOC autoanalyser (Multi N/C 3100, Jena Analytik). The difference in total N between extracts of fumigated and unfumigated soils (N_{FE}) was used for SMBN estimation: SMBN = 0.54 × N_{FE} ($mg \cdot kg^{-1}$) (Brookes et al. 1985; Tonon et al. 2005).

Determination of soil properties

Soil samples collected each season were air-dried, ground and passed through a 0.5-mm sieve. The total N contents (N_T) of both surface (0–10 cm) and deep (11–30 cm) soil were analyzed using an Auto-Kjeldahl Analyzer. The total contents of soil organic C (SOC) were determined by Walkley-Black wet oxidation (Nelson and Sommers 1982). Soil pH was determined using a Horiba-173 pH meter in distilled water (soil:water ratio of 1:2.5) after end-over-end shaking for 1 h and a settling time of 15 min.

Water contents (%) of soil samples by forest stand and depth were determined gravimetrically every season. Bulk density was determined only once at the beginning of the study. A total of 12 soil cores per stand were used to estimate soil bulk density (0–30 cm soil layer).

Forest floor included the fine materials, such as leaf litter and small branches (<2.5 cm in diameter). The forest floor profile was divided into litter (L), fermentation (F), and humified (H) layers. To account for the seasonal variations in forest floor properties, six samples were randomly collected in each forest stand seasonally (annually four times). Forest floor organic matter was collected using a 50 × 50 cm frame. L, F, and H layers were separated in the field at the time of collection. Samples for chemical analysis were extracted and returned to the laboratory in plastic bags. All samples were oven dried at 70°C to constant weight, then weighed and ground. The total N and C concentrations were determined by the above-mentioned methods.

Statistical analyses

We used one-way analysis of variance (ANOVA) to analyze the effects of forest age on soil and forest floor properties. Within each stand, the average rates of N mineralization and nitrification were compared by soil horizon. Where ANOVA indicated a significant difference ($p < 0.05$), means were separated using Duncan's multiple range test (StatSoft Inc. 2004).

In order to investigate the internal and external controls over N dynamics, annual rates of N mineralization and nitrification were correlated with soil and forest floor properties, and with each other using Pearson's correlation coefficient (StatSoft Inc. 2004). All statistical tests were considered significant at the $p < 0.05$ level.

Results

Properties of soil and forest floor

Soil property in forest stands differed by age of stand (Table 2). Soil bulk density was significantly lower in old stands (48-yr-old and 65-yr-old) than in young stands (18-yr-old and 36-yr-old). Soil pH was lowest in the 65-yr-old stand. The concentrations of SOC, total N, and available P were higher in old stands (48-yr-old and 65-yr-old) than in young stands (18-yr-old and 36-yr-old). The lowest concentrations of SOC and total N in the top 30-cm soil were found in the youngest stand (18 yr). Soil C:N ratio was highest in the 18-yr-old stand and lowest in the 48-yr-old stand for the 0-10 cm soil layer (Table 2).

Table 2. Soil properties of 18-65 year old forest stands in Laoshan Nature Reserve in Eastern China

Forest stand	pH (H_2O)		Total org-C ($g \cdot kg^{-1}$)		Total N ($g \cdot kg^{-1}$)		C:N ratio		Available P ($mg \cdot kg^{-1}$)		Bulk density ($g \cdot cm^{-3}$)	
	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm	0-10 cm	10-30 cm
18 year	4.58	4.72	39.61	13.71	2.77	1.22	14.31	11.24	9.39	6.29	1.16	1.27
	(0.13)ab	(0.11)a	(2.48)a	(1.16)a	(0.14)a	(0.13)a	(0.22)a	(0.16)ab	(1.35)a	(1.09)a	(0.03)a	(0.04)a
36 year	4.51	4.68	41.73	18.16	2.69	1.66	15.51	10.94	14.37	7.46	1.11	1.23
	(0.11)a	(0.12)a	(2.98)a	(1.45)b	(0.11)a	(0.09)b	(0.27)b	(0.18)a	(1.49)b	(1.13)a	(0.03)b	(0.04)a
48 year	4.66	4.81	50.47	23.29	3.96	2.07	13.04	11.25	23.84	9.69	1.07	1.18
	(0.10)b	(0.10)b	(2.19)b	(1.82)c	(0.15)b	(0.10)c	(0.23)c	(0.19)ab	(2.09)c	(1.21)b	(0.03)b	(0.03)b
65 year	4.31	4.46	57.73	25.19	4.25	2.18	12.64	11.56	26.92	12.28	1.03	1.17
	(0.10)c	(0.12)c	(2.47)d	(1.69)c	(0.17)c	(0.11)c	(0.31)c	(0.29)b	(2.12)d	(1.26)c	(0.03)c	(0.03)b

Values are means with S.E. in parenthesis. Means with different letters within rows are statistically different at $p < 0.05$.

Forest floor properties varied across the different stands (Table 3). The total mass was significantly higher in 48-yr-old and 65-yr-old stands than in 18-yr-old and 36-yr-old stands. The F+H layer was well-developed in the oldest stand (65–yr-old). Total C concentration in the L layer exhibited no differences among different stands but differed in the F+H layer. However, total N concentration in the L layer was significantly lower in 18-yr-old stand than in all other stands. Total C and N storage on the forest floor were similar in 48-yr-old and 65-yr-old stands. Total C and N storage were significantly greater in 48-yr-old and 65-yr-old stands than in 18-yr-old and 36-yr-old stands (Table 3). The C:N ratio in the L layer was lower in the 65-yr-old stand than in all other stands. The C:N ratios for the F+H layer (32-33) and the average for the forest floor (40-41) were similar amongst 36-, 48- and 65-yr-old stands. C:N ratios for the 18-yr-old stand (36 for F+H layer and 44 for forest floor average; Table 3) were

significantly higher than for all other stands.

Table 3. Properties of forest floor in 18-65 year old forest stands in Laoshan Nature Reserve in Eastern China

Forest stand	Dry Mass (Mg·ha^{-1})			Total C (Mg·ha^{-1})			Total N (kg·ha^{-1})			C:N ratio		
	L layer	(F+H) layer	Total	L layer	(F+H) layer	Total	L layer	(F+H) layer	Total	L layer	(F+H) layer	Mean
18 year	5.63 (1.13)a	2.08 (0.25)a	7.71 (1.26)a	2.79 (0.24)a	0.87 (0.12)a	3.66 (0.25)a	59.19 (6.80)a	24.56 (2.46)a	83.75 (8.01)a	47.08 (1.72)a	35.65 (1.29)a	43.72 (1.43)a
36 year	5.89 (0.97)ab	3.68 (0.27)b	9.57 (1.33)b	2.98 (0.31)ab	1.51 (0.16)b	4.49 (0.24)b	63.92 (7.09)a	46.11 (5.13)b	111.03 (8.93)b	46.63 (1.56)ab	32.80 (1.37)b	40.83 (1.51)b
48 year	7.03 (1.21)bc	4.86 (0.36)c	11.89 (1.46)c	3.54 (0.32)bc	1.99 (0.19)c	5.53 (0.29)c	76.01 (7.28)b	61.05 (6.51)c	137.06 (9.29)c	47.07 (1.63)a	32.56 (1.33)b	40.61 (1.46)b
65 year	7.41 (1.19)c	4.89 0.33)c	12.30 (1.41)c	3.75 (0.37)c	1.99 (0.18)c	5.74 (0.30)c	82.19 (7.59)c	61.75 (6.37)c	143.94 (9.58)c	45.62 (1.53)b	32.31 (1.37)b	39.91 (1.31)b

Values are means with S.E. in parenthesis. Means with different letters within rows are statistically different at $p < 0.05$.

Seasonal patterns of soil N availability and N mineralization

Soil N availability differed between stands (Fig. 1). The mineral N pool was small for the youngest stand (less than 4 mg N·kg^{-1} all year) and large for the oldest stand (mean 17.78 mg N·kg^{-1}). The concentration of NO_3^--N was low in all stands all year with a range of 0.41–2.65 mg·kg^{-1} for 0–10 cm and 0.28–1.76 mg·kg^{-1} for 11–30 cm mineral soil, indicating that the rate of nitrification rate in this forest is slow.

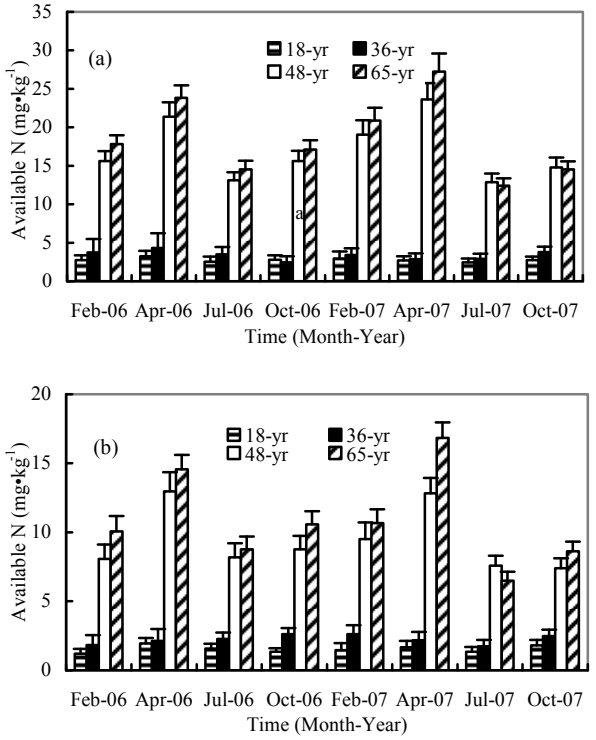

Fig. 1 Changes of available N (NH_4^+-N + NO_3^--N) by stand age in 0–10 cm (a) and 11–30 cm (b) horizons of the mineral soil in four stands of subtropical evergreen broad-leaved forest during 2006–2007. Error bars represent S.E.

The contents of soil microbial biomass N (SMBN) averaged from 60.65 to 77.51 mg·kg^{-1} for the 0–10 cm soil layer and 39.16 to 52.93 mg·kg^{-1} for the 11–30 cm soil layer. SMBN generally differed significantly by stand age in both soil layers. The exception was seen between 18-yr-old stands and 36-yr-old stands in the 0–10 cm soil layer, where SMBN was similar (Fig. 2). SMBN did not vary between the two years of study for in either soil layer.

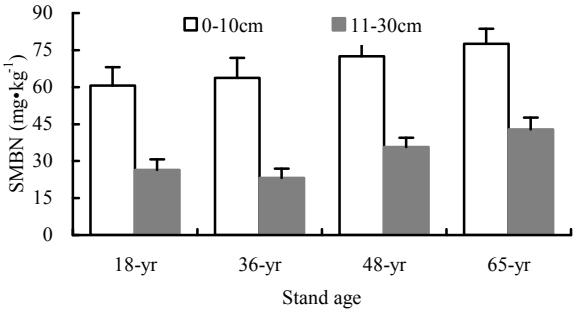

Fig. 2 Soil microbial biomass N by soil layer in four age classes of subtropical evergreen broad-leaved forest during 2006-2007. Error bars represent S.E.

Soil N mineralization and nitrification rates showed remarkable seasonal dynamics. For all stands studied, soil N mineralization and nitrification rates were higher in summer and lower in winter (Fig. 3). The annual mean rates of net N mineralization ranged from 311.72 to 424.66 μg·kg^{-1} soil·d^{-1} for the 0–10 cm soil layer and 180.79 to 253.18 μg·kg^{-1} soil·d^{-1} for the 11–30 cm soil layer. The net rate of soil nitrification was consistently low in stands, with annual means of 92.44–109.06 μg·kg^{-1} soil·d^{-1} for the 0–10 cm soil layer and 49.53 to 55.23μg·kg^{-1} soil·d^{-1} for the 11–30 cm soil layer (Fig. 4). Net N mineralization differed between stands (all $p < 0.031$). However, the differences in soil nitrification were not significant except between 36-yr-old and 48-yr-old stands ($p = 0.017$) and between 36-yr-od and 65-yr-old stands ($p = 0.019$).

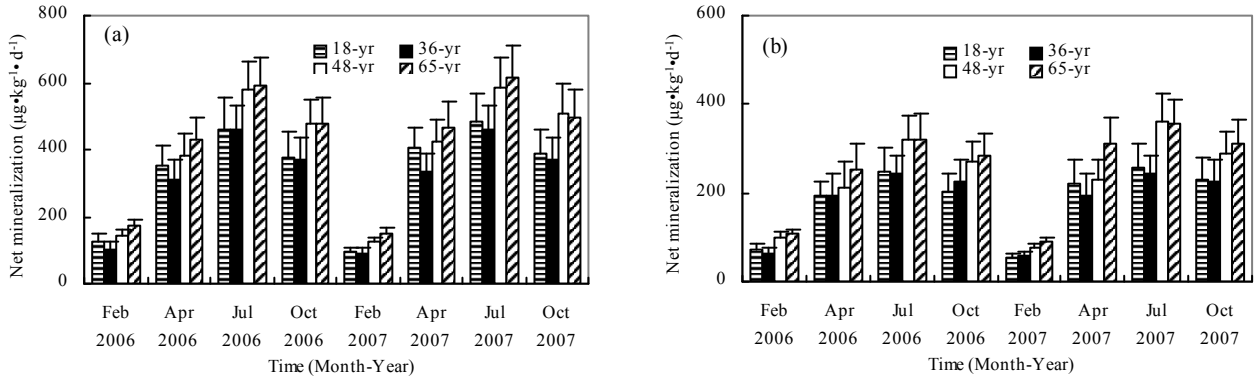

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Fig. 3 Net rates of N mineralization in the 0−10 cm (a) and 11−30 cm soil layers (b) in four age classes of subtropical evergreen broad-leaved forest during 2006−2007. Error bars represent S.E.

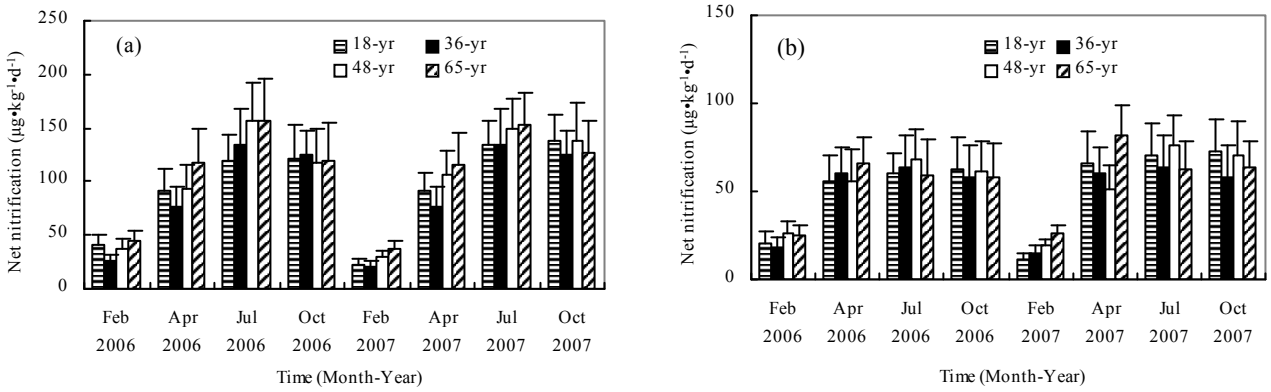

Fig. 4 Net rates of N nitrification in the 0−10 cm (a) and 11−30 cm (b) soil horizons in four age classes of subtropical evergreen broad-leaved forest during 2006−2007. Error bars represent S.E.

Nitrification as a proportion of N mineralization also varied with stand age. On an annual basis, nitrification was 0.298 of N mineralization in the 18-yr-old stand. For the 65-yr-old stand, nitrification was approximately 0.228 of N mineralization.

Relationships of N mineralization and nitrification with soil properties

Linear regression analysis showed that both net N mineralization and net nitrification in the 0–10 cm soil horizon were significantly and positively correlated with soil moisture, inorganic N pool, and SMBN, and were negatively correlated with forest floor and soil C:N ratios (Table 4). For the 11–30 cm soil layer, both net N mineralization and net nitrification were significantly and positively correlated with soil moisture and SMBN, and were negatively correlated with forest floor C:N ratio. However, no significant correlations were detected between soil C:N ratio, net N mineralization (p = 0.442), and net nitrification rates (p = 0.976) (Table 5).

Table 4. Pearson correlation coefficients for the relation between soil N mineralization (Rmin) and nitrification rates (Rnit) and soil properties for 0−10 cm layer in Laoshan Nature Reserve in Eastern China

	Forest floor C/N ratio	IN pool	SMBN	Soil moisture	Rmin	Rnit	RN
Soil C/N ratio	0.649	-0.706*	-0.846**	-0.982***	-0.945***	-0.942***	0.760*
Forest floor C/N ratio		-0.845**	-0.853**	-0.633	-0.805*	-0.763*	0.809*
IN pool			0.930***	0.715*	0.860**	0.747*	0.929***
SMBN				0.830*	0.920***	0.895**	-0.832**
Soil moisture					0.959***	0.945***	-0.788*
Rmin						0.952***	-0.903**
Rnit							-0.742*

Note: RN, relative nitrification; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Table 5. Pearson correlation coefficients for the relation between soil N mineralization (Rmin) and nitrification rates (Rnit) and soil properties for 11−30 cm layer in Laoshan Natural Reserve in Eastern China

	Forest floor C/N ratio	IN pool	SMBN	Soil moisture	Rmin	Rnit	RN
Soil C/N ratio	0. 161	0.337	0.148	0.389	0.319	0.089	-0.327
Forest floor C/N ratio		-0.844**	-0.817**	-0.772*	-0.874**	-0.745*	0.784*
IN pool			0.808*	0.828*	0.888**	0.456	-0.942***
SMBN				0.903**	0.968***	0.811*	-0.886**
Soil moisture					0.954***	0.725*	-0.929***
Rmin						0.778*	-0.924***
Rnit							-0.535

Note: RN, relative nitrification; *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$.

Discussion

Soil N mineralization involves biological processes that are controlled by soil temperature and moisture (Dalias et al. 2002; Knoepp and Swank 2002). Our results showed remarkable seasonal dynamics for the rates of soil N mineralization and nitrification. The rapid increase of soil N transformation rates in summer (higher temperature and moisture), and the rapid decrease in winter (lower temperature and moisture) can be explained by seasonal changes in soil temperature and water availability. These changes regulate soil microbial activity (Nicolardot et al. 1994; Knoepp and Swank 2002).

In forest ecosystems, soil N cycling can be impacted by soil properties and the quality of organic matter input (Compton and Boone 2002; Grenon et al. 2004), which are likely to change during forest succession (Verchot et al. 2001; Li et al. 2004; Pérez et al. 2004). Our results showed that surface soil and forest floor properties varied considerably during forest succession (Table 2). Generally, soil bulk density, soil pH, and surface soil and forest floor C:N ratios decreased over time, whereas soil total N and total organic C, available P, soil microbial biomass N, and forest floor mass increased over time (Tables 2 and 3). Li et al. (2004) demonstrated that forest degradation due to timber harvest rendered the ecosystem more abiotically controlled. Scott et al. (1997) found that net N mineralization was controlled by the quality of forest litterfall (C:N or lignin:N ratio) because this influenced the organic matter quality of soils. Therefore, soil and forest floor properties could play important roles in regulating N transformation during forest succession (Ross et al. 2004; Ste-Marie and Houle 2006).

Soil nitrification is usually controlled by the availability of soil ammonium (Robertson 1982), thus soil ammonification and the fate of soil ammonium are the most important factors determining the nitrification rate. Our findings demonstrated that soil pools were much greater for NH_4^+-N than for NO_3^--N, and that the soil nitrification rate was low in all stands (Fig. 2). This suggests a specific soil nitrification process in this subtropical forest. At our study site, sprouting regeneration after harvest is predominant (Lan et al. 2008), suggesting a possibly higher potential for N uptake by the regenerating vegetation. Therefore, high growth rates of trees and rapid N uptake may increase competition for available N in soils. This would slow soil accumulation of ammonium and result in low nitrification rates.

Patterns of N mineralization varied significantly by depth of soil horizon. The mean rates of net N mineralization and nitrification were consistently higher in the 0-10 cm horizon than in the 11-30 cm horizon for the same stand. This should be attributed mainly to the substrate quality and quantity. Field estimates of net N mineralization and nitrification showed marked seasonality in this subtropical forest, with higher rates during the summer months. However, no significant differences were found in N mineralization patterns between years (all $p > 0.152$). In addition, the mean rates of net N mineralization and nitrification were consistently higher in the old stand than in the younger stands. Similar results were reported by Idola et al. (2003) and Lindo and Visser (2003). Two earlier studies showed that N mineralization increased after forest harvest (Frazer et al. 1990; Prescott 1997), which could be attributed to the higher growth and turnover rates of fine roots in the younger forest stands (Idol et al. 2000).

Our results support the generally held conclusion that relative nitrification declines with stand age. However, net nitrification rates were still slightly higher in the older forest stands, probably due to the high rates of N mineralization or higher competition with plants and the microbial community for NH_4^+-N. Li et al. (2004) reported a similar pattern for the montane rainforests in southwestern China. In both studies N mineralization and nitrification rates were measured in the absence of plant uptake and N deposition, indicating that the inherent properties of the soils determined N cycling rates. Nevertheless, over the long run, soil properties can be regulated by litterfall and throughfall N inputs stimulating N mineralization (Fenn et al. 2005). At a site with high N deposition, Ouyang et al. (2007) found a very high nitrification rate (relative nitrification >70%) for all stands along a forest successional gradient in Dinghushan Nature Reserve, south China. This indicates that soil N cycling processes can be regulated by both the external and internal N inputs in forest ecosystem.

In conclusion, our study showed that surface soil and forest floor properties varied considerably between stands of increasing age. Total soil N, the mineral N pool, and soil microbial biomass N increased with stand age. Net rates of N mineralization and nitrification were significantly higher in older stands than in younger stands (all $p < 0.031$). The relative nitrification was low in this subtropical forest and declined with stand age. Our results provide evidence that management disturbances cause changes in

N cycling properties and processes in forest ecosystems.

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